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Observations of ionization phenomena made during the last few years by American and German physicists at different altitudes, in ice caverns and below the surface of mountain lakes, as well as on balloon flights, have proved definitely that some sort of hard, highly penetrating radiation with a detectable spectral distribution enters the atmosphere from the depths of the Universe. There is some discrepancy between the results of different scientists, and some differences in the explanations that have been suggested. Kolhörster, for example, found that the maximum ionization was detected by his apparatus when the Milky Way crossed the zenith,[1] but the recent reinvestigation of penetrating radiation by Millikan and Cameron[2] did not reveal any preferential direction in the heavens from which the rays come, and demonstrated that within the limits of uncertainty of measurement the penetrating rays shoot through space with equal intensity in all directions. Another difficult point is the existence of some sort of secondary radiation of which the explanation is still controversial.

For the astrophysicist the discovery of cosmic penetrating radiation is important and interesting in two respects. In the first place the problem of the origin of this radiation is intimately connected with the question of the source of stellar energy. Many valuable suggestions and conjectures have been made during the last few years on this subject, and penetrating radiation has provided a wide and inviting playground for different hypotheses and speculations.

There is also another point of interest. We may conclude from recent data that penetrating radiation forms a general field of energy, without detectable anisotropy, which is superposed on many local fields of various strengths, as the general gravitational field of the galaxy is superposed on the local fields due to individual stars or clusters. The general field of very penetrating radiation, similar to the hardest γ rays from Radium C, may have a large ionizing effect for nebulae and cosmical clouds of small optical thickness. The scattering of such rays by the free and bound electrons of a light nebular gas would create very swift β particles as well as ions, and the repeated impacts between atoms and swift electrons would further increase the ionization and partial excitation. The nebular gas

would thus become excited by an "invisible" agent, which would stimulate its radiation. During the past few years it has frequently been questioned whether the radiation of the bright diffuse nebulae and the planetaries can be explained by the existence of a general field of penetrating radiation, which could also be regarded as the cause of the enigmatic ionization in cosmic clouds of ionized calcium.

There may be two different causes of the ionization in nebulae: stellar radiation and penetrating radiation. These causes must be analyzed separately, and the chief aim of this paper is to discuss the second one. I shall investigate only the effect of the general field of penetrating radiation, as revealed by the experiments of Kolhörster and Millikan, neglecting possible local fields. Anticipating the results of a mathematical analysis based on the modern theory of scattering as well as on the theory of β and γ ionizations, we may state that the effect of the general field is always negligible in comparison with the stimulating effect of stars in all possible cases—not only for Eddington's interstellar gas, but also for planetary and bright diffuse nebulae.

Intensity of the General Field of Penetrating Radiation

In calculating the intensity of the general field of penetrating radiation we shall base our work upon the experimental data collected by Millikan two years ago at Muir Lake, 3590 m. above sea level. Millikan used the Compton formula for the mass absorption coefficient of X rays, which is valid for the hardest radiation of Radium C and Thorium D, as recently demonstrated by Ahmad, and discussed the data on the variation of ionization as a function of height above sea level. He was able to demonstrate that the spectrum of cosmic radiation begins at $\lambda = 6.34 \times 10^{-4}$ Å, and ends at $\lambda = 3.8 \times 10^{-4}$ Å, corresponding to the absorption coefficients 5.7×10^{-3} and 1.6×10^{-3}. Millikan found that at the height of Muir Lake the cosmic penetrating radiation is responsible for the formation of 12.2 ions per cubic centimeter per second. Millikan's observations showed that this phenomenon is a very complex one; in particular the origin of the soft radiation, which increases in intensity with height, seems to be unexplained, if we reject as unlikely the hypothesis of increasing γ radiation from the high rocks.

The average recoil electron after collision with a high frequency quantum will have a very large speed. We may therefore suppose that the only result of the impact of that electron with a neutral atom

or molecule is an ionization; in a steady state therefore all the penetrating radiation absorbed (in consequence of scattering) is spent on the formation of ions. In reality the greater part of the absorbed energy will be carried away by swift recoil electrons without any ionization. The range of the average recoil electron, according to Millikan's calculations, is 52 meters in air, equivalent to 5.1 mm. of brass. If however we consider the steady state, we may suppose that this outflow is balanced by a corresponding inflow, which is equivalent to making the supposition that the hypothetical electron stream that maintains the earth charge, according to Swann,[3] and is produced by cosmic penetrating radiation, is steady. We shall therefore adopt as an experimental result that at the height of Muir Lake the energy of the absorbed cosmic radiation is equal to 12.2 ε, where ε is the energy corresponding to the formation of one ion in air. On the other hand, according to Compton's theory,[4] for a given frequency the true absorption due to the scattering per cubic centimeter per second is

$$s = \sigma \frac{\alpha}{(1 + 2\alpha)^2}$$

where

$$\alpha = \frac{h\nu}{mc^2} = \frac{0.0242}{\lambda},$$

λ being expressed in Angstrom units. The quantities h, e, m, and c are Planck's constant, the charge of an electron, the mass of an electron, and the velocity of light, respectively. Thomson's scattering coefficient σ is equal to

$$\frac{8}{3\pi} \frac{e^4}{m^2 c^4} n = 6.10 \times 10^{-25} n,$$

where n is the number of scattering centers. For the lighter elements and hard radiation n is equal to the sum of the number of free and bound electrons because in this case, owing to the relatively weak bond between electrons and nuclei the bound electrons will scatter as if they were quite free. For the lighter elements we may therefore adopt $\sigma = 6.10 \times 10^{-25} ZN$, where Z is the atomic number, and N the number of atoms in a cubic centimeter.

As we know nothing about the distribution of intensity in the spectrum of penetrating radiation we shall suppose that the intensity $I(\nu)$ is uniform between ν_1 and ν_2, the observed extremities of Mil-

likans spectrum, so that $I(\nu)d\nu = \gamma d\nu$. The whole absorption due to scattering will therefore be

$$\sigma\gamma\int_{\nu_1}^{\nu_2}\frac{\alpha}{(1+2\alpha)^2}\,d\nu$$

Integrating, and setting the full absorption equal to the energy of ionization, we get for Muir Lake

$$\sigma\gamma\frac{mc^2}{2h}\left[\frac{\alpha+\alpha^2}{(1+2\alpha)}-\tfrac{1}{2}\log(1+2\alpha)\right]_{\alpha_1}^{\alpha_2}=12.2\,\varepsilon, \qquad (1)$$

where

$$\alpha_{1,2}=\frac{h\nu_{1,2}}{mc^2}.$$

We shall use the experimental data of Barkla, who found that for air under atmospheric pressure Thomson's scattering coefficient for X rays is $\sigma = 0.00025$. For the height of Muir Lake we therefore have $\sigma = 1.7 \times 10^{-4}$. It is somewhat difficult to evaluate ε for air. According to Smyth[5] the successive ionization potentials of molecular nitrogen by electronic impact closely resemble those for oxygen, as shown below.

Ionization Potential	Product	Nitrogen volts	Oxygen volts
χ_1	Singly charged molecular ions	16.9	15.5
χ_2	Doubly charged atoms	24.1	22.5
χ_3	Singly charged atoms	27.7	23.0

The succession of states mentioned in the table is not too customary for the astrophysicist. Normal ionization in the upper atmosphere is connected with χ_1, inasmuch as the well known negative band of nitrogen is emitted by positive molecules, and the lines of atomic nitrogen have not been detected in the spectrum of the aurora. On the other hand atomic oxygen, according to McLennan[6] gives the green auroral line. We shall therefore adopt that the ionization in air corresponds to a value between χ_1 and χ_2.

The penetrating radiation is very hard, and the recoil electrons are very swift; it is therefore impossible to foresee the effect of a successful encounter between quanta, electrons, and nitrogen atoms, for example, or to calculate the stage of the resulting ionization. Fortunately we do not need the value of χ, but only that of ε, the energy

of ionization per ion, and this quantity remains nearly the same for different ionization potentials—between ten and twenty volts.

From formula (1) we calculate

$$\gamma = 2.6 \times 10^{-27} \text{ for } \chi_1, \quad \text{and} \quad \gamma = 4.0 \times 10^{-27} \text{ for } \chi_2.$$

At the limit of the atmosphere γ will of course be larger. If we suppose that the mass absorption coefficient for penetrating radiation is the same for all frequencies, and equal to that for $(\nu_1 + \nu_2)/2$, and adopt the value given for it by Millikan, we can calculate γ at the limit of the atmosphere by inverting Millikan's method. Supposing that the rays enter the atmosphere equally from all directions, and denoting by H the distance below the top of the atmosphere, and by μ the absorption coefficient, we have

$$d\gamma = \gamma_0 2\pi e^{-\mu H \sec\theta} \sin\theta \, d\theta$$

and integrating,

$$\gamma = \gamma_0 2\pi \int_1^\infty \frac{e^{-\mu H x} dx}{x^2}$$

Adopting for a meter of water $\mu = 0.36$ and in meters of water for Muir Lake $H = 6.8$, we finally find

$$\gamma_0 = 5.8\,\gamma = 15.1 \times 10^{-27} \text{ for } \chi_1, \quad \text{or} \quad 23.2 \times 10^{-27} \text{ for } \chi_2.$$

The full flux of energy in ergs through one square centimeter at the limiting surface of the atmosphere is

$$I_0 = \gamma_0(\nu_2 - \nu_1) = \gamma_0\left(\frac{c}{\lambda_2} - \frac{c}{\lambda_1}\right) = \gamma_0\, 3.1 \times 10^{21}$$

$$= 4.7 \times 10^{-5} \text{ for } \chi_1, \quad \text{and} \quad 8.2 \times 10^{-5} \text{ for } \chi_2.$$

For interstellar space I_0 must be twice as great.

It is interesting to compare with this the flux of solar energy at unit distance, which, adopting Abbot's value of the solar constant, is 1.4×10^5 ergs per square centimeter per second. Notwithstanding its small bolometric value (which is 10^{-10} of that for the sun's rays) the penetrating radiation, in consequence of its ionizing power, plays an important rôle in the physics of the earth, since it is very probably the cause of the maintenance of the earth's macroscopic charge.

Astrophysical Applications

Consider a rarefied gaseous layer in the field of penetrating radiation, and neglect the stimulating influence of star light. Since the monochromatic absorption coefficient is proportional to ν^{-3}, we may suppose that the only form of interaction between such hard radiation and matter is Compton scattering.

The energy caught by electrons is spent upon ionization and on diffusion of swift electrons; in a steady state the latter may be neglected. In such a case the only process counterbalancing the inflow of energy is photoelectric emission during the capture of free electrons by the nuclei. The hypothetical three body encounters, which, according to Fowler, balance the ionizations by collision in thermodynamic equilibrium, are useless in the present case, because of the low density of the nebular gas.

Suppose the distribution of the velocities of free electrons to be Maxwellian, denoting by Nx the number of atoms ionized, we find that the number of electrons with velocities between v and dv meeting ionized atoms at a distance between p and $p + dp$, is

$$8\pi^2 Nx \left(\frac{m}{2\pi k T_0}\right)^{3/2} e^{-\frac{1}{2}\frac{mv^2}{kT_0}} v^3 \frac{dp^2}{2} dv$$

where k is Boltzmann's constant, and T_0 is the "temperature" corresponding to the energy of the electrons. The total number of encounters for a given v will be

$$8\pi^2 N^2 x^2 \left(\frac{m}{2\pi k T_0}\right)^{3/2} e^{-\frac{1}{2}\frac{mv}{kT_0}} F(v) v^3 dv$$

where $F(v) = \int_0^{p_0} f(v, p) p\, dp$ and is half the square of the atomic radius, and $f(v, p)$ is the probability of a capture during a (v, p) encounter. In this case the atom emits one quantum, whose energy as determined by Einstein's equation, is

$$h\nu = \tfrac{1}{2}mv^2 + h\nu_0 = \tfrac{1}{2}mv^2 + \chi_0$$

where χ_0 is the ionization potential. Therefore the full radiation per cubic centimeter per second will be

$$8\pi^2 x^2 N^2 x^2 \left(\frac{m}{2\pi k T_0}\right)^{3/2} h \int_0^\infty \nu e^{-\frac{1}{2}\frac{mv^2}{kT_0}} v^3 F(v) dv$$

For $F(\nu)$ we may adopt the formula of Kramers[7]

$$F(\nu) = \frac{C}{\nu^2 \nu},$$

where

$$C = \frac{32\pi^3 g' Z^4 e^{10}}{3\sqrt{3}\, mh^4 c^3}\left[\frac{1}{(n-\frac{1}{2})^2} - \frac{1}{(n+\frac{1}{2})^2}\right]$$

$g' = 2.3$, n is the total quantum number for a given level. For hydrogen, having only one quantum state, $Z = 1$, $n = 1$, $C = 1.71 \times 10^{10}$.

Calculation of the total emission in the case of an atom having only one quantum state gives

$$\frac{4\pi x^2 N^2 m^{1/2} hC}{(2\pi k T_0)^{1/2}}$$

Equating this to the full absorption due to scattering, as given by formula (1), we find

$$\frac{4\pi x^2 N^2 m^{1/2} hC}{(2\pi k T_0)^{1/2}} = \gamma_0 \sigma_0 ZN \frac{mc^2}{2h}\left[\frac{\alpha + \alpha^2}{(1+2\alpha)} - \tfrac{1}{2}\log(1+2\alpha)\right]_{\alpha_1}^{\alpha_2}$$

We have used here $2\gamma_0$ instead of γ_0 for the earth, because in the present case the gaseous layer is exposed to the full penetrating radiation of interstellar space. Setting $N = \rho/M$, where ρ is the density and M the mass of the atom, we finally find

$$\frac{x^2\rho}{T_0^{1/2}} = A_1 \tag{2}$$

where A_1 is a known function of atomic constants, equal to

$$\frac{\gamma_0 \sigma_0 m^{1/2} c^2 (2\pi k)^{1/2} M}{8\pi h^2 C}\left[\frac{\alpha + \alpha^2}{1+2\alpha} - \tfrac{1}{2}\log(1+2\alpha)\right]_{\alpha_1}^{\alpha_2}$$

Equation (2) is the equation of radiative equilibrium.

It remains to find the equation of statistical equilibrium, which expresses that the total number of ionizations is equal to the total number of captures. The total number of captures for atoms with only one quantum state, according to what precedes, is

$$\frac{8\pi^2 x^2 \rho^2}{M^2}\left(\frac{m}{2\pi k T_0}\right)^{3/2} \int_0^\infty e^{-\frac{1}{2}\frac{m v^2}{k T_0}} v^3 F(\nu) d\nu$$

Introducing Kramers' expression for $F(v)$ and integrating, we find, for the total number of captures

$$-\frac{8\pi^2 x^2 \rho^2}{M^2}\frac{m^{1/2}Che^{\frac{h\nu_0}{kT_0}}}{(2\pi kT_0)^{3/2}}E\left(-\frac{h\nu_0}{kT_0}\right)$$

$E(-z)$ is a logarithmic integral, equal to

$$-\int_1^\infty \frac{e^{-zx}dx}{x}.$$

The total number of ionizations by electronic impact may be calculated according to the theory of R. H. Fowler.[8] Although Fowler calculated his probability coefficients by assuming detailed balancing in the condition of thermodynamic equilibrium, they nevertheless express some atomic properties independent of the macroscopic behavior of the gas, and may therefore be applied in our case. According to Fowler's theory the total number of ionizations by electronic impact is

$$\frac{8\pi\Delta\rho^2 x(1-x)e^{-\frac{h\nu_0}{kT_0}}}{M^2(2\pi kT_0)^{3/2}m^{1/2}}\int_0^\infty\left(\frac{1}{h\nu_0}-\frac{1}{h\nu_0+z}\right)e^{-\frac{z}{kT_0}}dz$$

where, with some uncertainty, the classical value $\Delta = \pi e^4$ may be adopted for Δ. Integration gives

$$\frac{8\pi^2 e^4\rho^2 x(1-x)e^{-\frac{h\nu_0}{kT_0}}}{M(2\pi kT_0)^{3/2}m^{1/2}}\left[\frac{kT_0}{h\nu_0}+e^{\frac{h\nu_0}{kT_0}}E\left(\frac{-h\nu_0}{kT_0}\right)\right]$$

Apart from these β ionizations there must be some γ ionization. The energy taken up by the recoil electron is enormously greater than the energy of ionization $h\nu_0$. The bound electrons, according to Compton's theory, will therefore scatter as if they were free, the important difference being that every elementary scattering will here be associated with an ionization. The total number of ionizations may be calculated by multiplying by $(1-x)/h\bar{\nu}$ the whole energy absorbed, where $h\bar{\nu}$ is the average value of the scattered quanta, and $1-x$ is the fraction of electrons in the bound state. This is correct for hydrogen, and also for other elements, if the second ionization potential is sufficiently high. The value of $h\bar{\nu}$ may be calculated in the following way, according to Millikan. Compton's theory gives, for the ratio between the mean energy in the scattered quant and the energy in the recoil electron, the value $(1+\alpha)/\alpha$, where $\alpha = h\nu/mc^2$

and is very high in our case—between 64 and 38. The ratio will therefore be near to unity; on the average each particular act of scattering divides the energy of the original quant equally between the new quant and the recoil electron. We may therefore adopt $h\bar{\nu} = h(\nu_1 + \nu_2)/4$, since the average quant, before scattering, was equal to $h(\nu_1 + \nu_2)/2$. The total number of γ ionizations will therefore be

$$\frac{2\gamma_0 \sigma_0 Z\rho mc^2 (1 - x)}{Mh^2(\nu_1 + \nu_2)} \left[\frac{\alpha + \alpha^2}{1 + 2\alpha} - \tfrac{1}{2} \log (1 + 2\alpha) \right]_{\alpha_1}^{\alpha_2}$$

Equating the total number of β and γ ionizations to the total number of captures, we obtain the following equation of statistical equilibrium

$$A_2 \rho e^y x^2 E(-y) = x(1-x)\rho e^{-y}(y^{-1} + e^y E(-y)) + \frac{(1 - x)}{y^{3/2}} A_3 \qquad (3)$$

where

$$y = \frac{h\nu_0}{kT_0}, \quad A_2 = -\frac{Chm}{e^4}, \text{ and}$$

$$A_3 = \frac{\gamma_0 \sigma_0 Z m^{3/2} c^2 M (2\pi)^{3/2} (h\nu_0)^{3/2}}{h^2(\nu_1 + \nu_2) 4\pi^2 e^4} \left[\frac{\alpha + \alpha^2}{1 + 2\alpha} - \tfrac{1}{2} \log (1 + 2\alpha) \right]_{\alpha_1}^{\alpha_2}.$$

For particular assumptions as to the density and chemical composition of the nebular layer the equations (2) and (3) allow us to find x and T_0, which characterize the state of the layer. If we consider, for the sake of simplicity, hydrogen in the normal state, then $h\nu_0 = 13.2rs = 2.1 \times 10^{-11}$ ergs a second. In thiscase $y = 1.5 \times 10^5 / T_0$, which is doubtless much greater than unity. We therefore use the following series

$$E(-y) = -\frac{e^{-y}}{y}\left(1 - \frac{1}{y} + \frac{2!}{y^2} - \cdots\right).$$

Calculating A_1, A_2, and A_3, we find the following equations for x and y, if we take, for the nebula, $\gamma_0 = 2 \times 18 \times 10^{-27} = 36 \times 10^{-27}$, $x^2 \rho y^{1/2} = 3.9 \times 10^{-30}$

$$\frac{1 - x}{x} \frac{e^{-y}}{y} + \frac{1 - x}{x^2} \frac{e^{-y}}{y^{1/2} \rho} 79 \times 10^{-53} = 2 \times 10^{-6}.$$

The ratio of the total number of γ ionizations to the total number of β ionizations is thus equal to $79 \times 10^{-53} y^{1/2} e^y / \rho x$, that is to say it is

very small, even if we make the boldest suppositions about x and ρ. This can be satisfactorily explained, because the number of atom-quant collisions is very small compared to the number of atom-electron impacts, the electrons spending their energy supply only slowly after many collisions with atoms. In what follows we shall neglect the γ ionizations.

Consider the ionization of interstellar gas, which has a density of 10^{-24}, according to Eddington.[9] In this case our equations give

$$x = 2 \times 10^{-3}, \quad \text{and} \quad y = 16$$

The energy of an average electron appears to correspond to an equivalent temperature of 10000°. We therefore see that the general field of penetrating radiation, producing high speed electrons, gives only a low degree of ionization to the interstellar gas. For the ionization in the stimulating field of general stellar radiation Eddington obtained a much greater value—for instance sodium is all in the Na+ state, and calcium all in the Ca++ state. According to his data the density of interstellar radiation is 8×10^{-13} ergs per cubic centimeter. The density of the penetrating radiation, (which is I_0/c) comes out, according to our calculations, as 4.2×10^{-15}. Inside a layer of planetary nebula, conditions are still less favorable to the penetrating radiation. If the nucleus is a normal O star with a bolometric absolute magnitude -4, its total radiation per square centimeter is 1.5×10^{38} ergs a second. At a distance of 10^{17} centimeters (corresponding to the average distance of the gaseous layer from the nucleus) the density of stimulating radiation inside a planetary is therefore of the order of 10^{-6}.

Radiative ionization within a planetary is therefore very large; for hydrogen $1 - x$ is here of the order of 10^{-6}. If, however, we adopt a density of 10^{-15} for these nebulae, our formulae show that for β and γ ionizations in the field of general penetrating radiation, x is vanishingly small, being of the order of 10^{-6}.

From the theoretical point of view it is not altogether surprising that the extremely hard cosmic penetrating radiation should be so ineffective. We know that the greater part of the ionization produced by penetrating radiation is caused by very swift electrons. But it is well known that the ionizing power of a β particle increases with speed only up to a certain point, and then falls. The theory of β rays shows[8] that the effective area for ionization by electronic impacts is proportional to $\frac{1}{\varepsilon}\left(\frac{1}{\varepsilon_0} - \frac{1}{\varepsilon}\right)$, where ε is the energy of an elec-

tron, and ε_0 that of an ionization. This effective area has a maximum for $\varepsilon = 2\varepsilon_0$, and decreases for larger values of ε. The maximum is relatively low; for the ionization of hydrogen gas by β particles it corresponds only to 26.4 volts.

The effects of the general field of penetrating radiation may be neglected. Its ionizing effect is very small in comparison with the effect of the general field of stellar radiation (Eddington's interstellar gas) or of hot stars (planetary and diffuse gaseous nebulae). The supply of high speed electrons created by penetrating radiation, though large, is of the same order as that created by stimulating stellar radiation (in the case of planetaries the value of T_0 for penetrating radiation is about 5000°). But we are dealing only with the general field of penetrating radiation, and our result does not allow us to assert that influence of this character is always negligible. It may be that in many parts of the Universe intense local fields of high frequency radiation are superposed on the general field, and these fields may of course produce ionization that is of high importance.

Hypothetical Local Fields

Let us consider a planetary or diffuse nebula, and suppose that there is some creation of penetrating radiation within the nebula itself. In analyzing the radiative equilibrium we must add to the left side of equation (1) a term which expresses the amount of penetrating radiation created in an element of volume. Instead of equation (1) we now obtain an inequality, the larger term being on the right hand side. We calculate the intensity of the local field, supposing that the resulting ionization is equal to that caused by the stimulating star, and that $1 - x = 10^{-6}$. The simple calculation shows that for a density of 10^{-19} the intensity of the corresponding local field must be 10^9 times larger than that of the general field, which is scarcely possible. This result shows that even if we may suppose that the nebular matter makes an appreciable contribution to the general field, we may always neglect its direct influence on the ionization within the nebula.

The other places where local fields of considerable strength might be expected are the atmospheres of certain stars. Consider a star of very low density, with a great supply of hydrogen. The transmutation of hydrogen into helium, or some higher element, will release energy of wave length 4.1×10^{-4} Å. The energy released in the relatively deep superficial layers will, after some scattering,

form a local field of penetrating radiation in the reversing layer or the chromosphere. Supergiants of Class M, and especially stars of the Mira Ceti type, exhibit the most favorable conditions for the formation of these local fields. Abnormally intense Balmer lines are the obvious manifestation of an abnormal supply of hydrogen; very low densities will result in small scattering. On the other hand the recently noted anomaly of the *M* supergiants—the behavior of the enhanced lines[10, 11] which can scarcely be explained by a normal deviation from thermodynamic equilibrium—together with a peculiar bright line spectrum, seem to be a natural consequence of such a local field.

Summary

1. By adopting the results of the reinvestigation of cosmic penetrating radiation by Millikan and Cameron, and assuming a steady state, it is calculated that the flux of penetrating energy outside our atmosphere is of the order of 10^{-5} ergs per square centimeter per second.

2. Considering a rarefied gaseous layer in the field of penetrating radiation, and supposing it to be in radiative and statistical equilibrium, adopting Kramers' theory of γ ionization and Fowler's theory of β ionization, it is shown that in all possible cases the ionization considered is very small in comparison with radiative ionizations due to the stars. For Eddington's interstellar gas (hydrogen) the percentage of atoms ionized is of the order of 10^{-2}. For planetary and diffuse nebulae it is of the order of 10^{-6}. The energy of the free electrons produced by the penetrating radiations is very high, but the effective area for ionization is relatively small for such swift β particles.

3. The local fields within nebulae, unless they are absurdly strong, cannot give effects of the order of those produced by stimulating stellar radiation. It is suggested that supergiants of Class M, having very low densities and large supplies of hydrogen, produce relatively strong local fields in their atmospheres, which may account for some of the peculiarities of these stars.

FOOTNOTES

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